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Pressure Tests in Soil below Tires of  
Agricultural Vehicles

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**SUMMARY** Design and measuring method of a cheap and efficient soil pressure gauge are described. Soil tank tests carried out in the laboratory demonstrate some properties of the gauge like indifference towards orientation in soil. In the soil bin the gauge measures pressures below tires rolling over and outside in the field the influence of wheel load, number of passes and vehicle speed are investigated. The results are interpreted with modified formulas of Soehne [1], which can be managed by a pocket calculator.

Introduction

Since Soehne [1], [2] and Chancellor [3] had done fundamental work on this subject in the beginning fifties, the amount of fertilization and the weight of agricultural machinery increased as well as the yield rates. Today chemical soil optimization had reached its boundaries and one looks after possibilities to improve soil structure. Von Boguslawski and Lenz [6] gave valuable advice to this problem. What did the farmer get from science to find out whether compaction is severe or not? He knows, that he has to avoid work under wet field conditions with heavy machinery and he uses the spade to estimate pore volume reduction. Perhaps it will be useful to provide him with reference values of pore volume reduction for several kinds of soils with several degrees of water content.

In view of this aim one has to get information about the range of soil stresses brought up by the actual agricultural machinery. To rise the number of data one has to select an efficient measuring procedure and the significant variables. Most common methods are bulk density and cone penetrometer measurement. Applying them, one has to concern the amount of work, the influencing parameters and the mission. The interdependence of bulk density, cone penetrometer resistance and water content together with varying kinds of soil imply a high number of experiments to get sufficient information in the field.

### Measuring Method

This arguments led to the consideration to measure the pressure in soil under the tires of agricultural vehicles, which is causal responsible for soil compaction. To find out the right procedure one has to observe several criteria. The most important are:

1. The gauge should be of a bulk density close to that of the soil, in order to avoid stress concentrations, if the gauge density is higher, or to avoid stress drop at the gauge, if the gauge density is lower.
2. The gauge application should cause a minimum of disturbances in soil and it should be possible in a justifiable range of time.

### two lance system

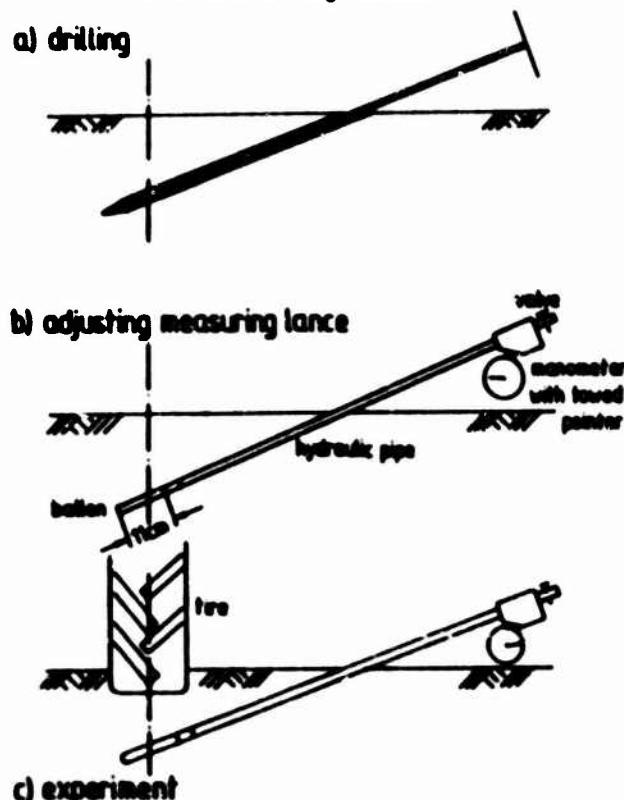


Fig. 1.: Principle and application of the pressure gauge

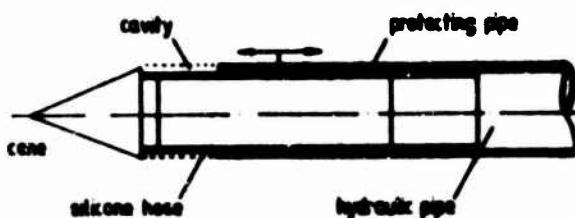
3. The gauge should measure defined stress components.
4. The gauge should be able to record the pressure during tire operation, to get information about dynamic effects.
5. Inexact gauge orientation in soil should cause minimum errors.
6. To use many gauges at the same time the costs must not be high.

Viewing the literature to this subject many valuable advices have been found for example in the works of Berdan [4], Cooper [5], Hovanesian [7], Barnes [8] and Blackwell [12]. The compromise made to observe most of the shown main criteria represents fig. 1:

A hole inclined about  $15^\circ$  -  $20^\circ$  to the surface is drilled into the soil, in which a pipe is pushed. A balloon with walls being 0,5 mm thick, a length of 11 cm and a diameter of 2 cm is turned out of the pipe by an air pump. Now the system is filled with water. This causes a gauge density of  $1 \text{ g/cm}^3$ .

### one lance systems

#### a) outer protecting pipe



#### b) inner supporting pipe

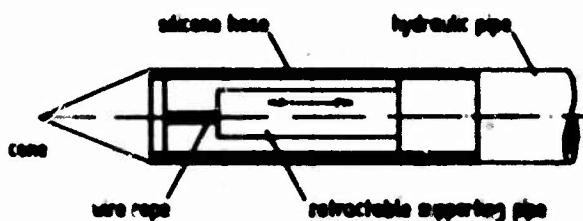


Fig. 2: Designs of one lance systems for simplified soil pressure gauge application

If a mixture of water and magnesium dichloride is used, higher densities are possible. With other fluids gauge densities between 1 and 2 g/cm<sup>3</sup> are conceivable, to accommodate gauge and soil density. When the air bubbles are pushed out of the system, the valve is closed and the experiment starts. When the tire rolls over the gauge, the pressure in the system rises. The maximum value can be recorded by a manometer with towed pointer or one can apply a usual pressure gauge with recording system to measure dynamic processes. To improve the handling abilities of this measuring principle, it was tried to design one lance systems shown in fig. 2. Here the three steps in fig. 1 are combined: The cone forms the hole in soil and when the protecting or supporting pipes are retracted, the fluid filled silicone hose with a wall thickness of 1 mm gets flexible similar to the balloon. The most significant advantage of the one lance system is, that turning out the proper gauge and filling the system with fluid is not necessary. Later more details will be described.

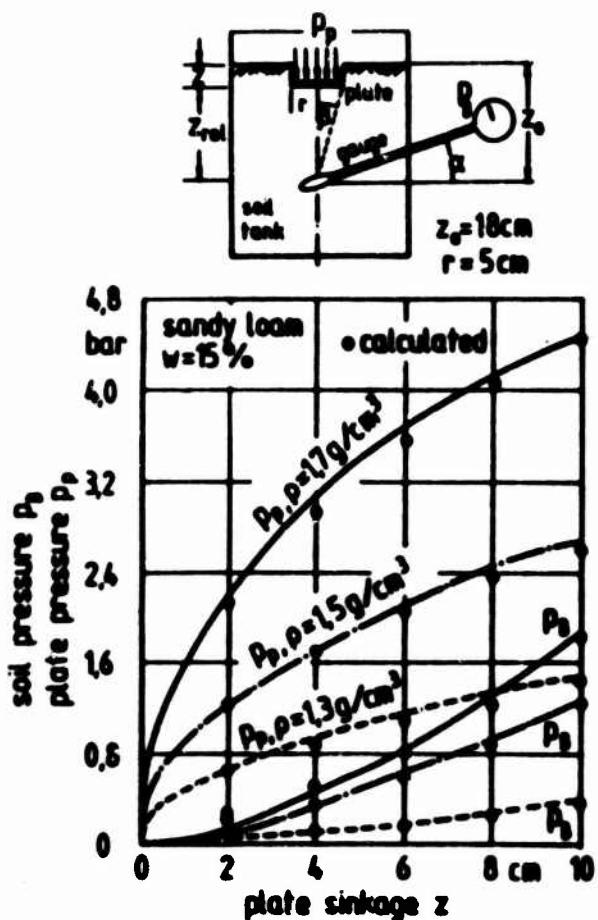


Fig. 3: Testing the pressure gauge in a soil tank with sandy loam of different dry densities

First the properties of the two lance system should be shown. In fig. 3 the curves of the soil pressure  $p_g$  in the gauge are plotted against the sinkage  $z$  of a circular plate moving into a tank with sandy loam of different densities. Increasing plate pressures  $p_p$  cause increasing gauge pressures  $p_g$ . With the bulk density the final values at  $z = 10$  cm of  $p_p$  and of  $p_g$  rise, whereas the characteristics of the curves don't change. (The water content was 15 %.)

Fig. 4 gives evidence of the tests varying the inclination  $\alpha$  of gauge and pipe. The influence is of the order of the variations caused by soil preparation. The reason may be, that the gauge is exposed to the varying

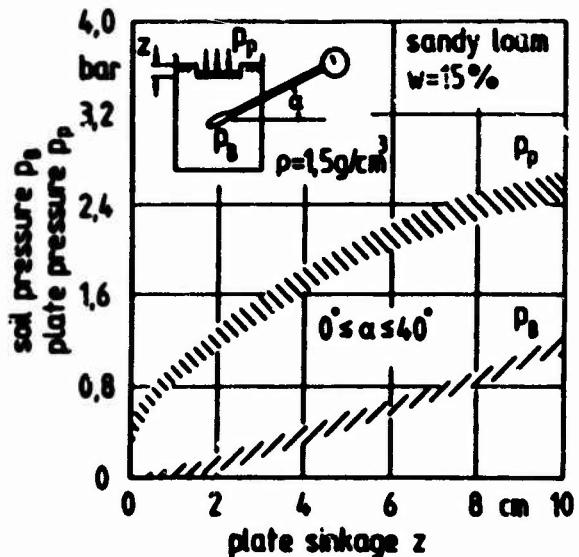


Fig. 4: Influence of gauge inclination  $\alpha$  on the measured pressure  $p_g$  in a soil tank with sandy loam

stresses on its surface and the manometer shows the mean value of all of them. So turning the cylindric gauge body round its center of gravity is of almost no effect in the range  $0^\circ \leq \alpha \leq 40^\circ$ . This fact is of advantage during work in field, because the rough terrain causes considerable errors of the measurement of the angle of inclination  $\alpha$ . Therefore one always has to excavate the gauge in field after the test to determine its real depth below the surface.

The record of the gauge pressure  $p_g$  during the roll over of a tire is plotted in fig. 5 against the position  $x$  of the tire relative to the gauge.  $p_g$  starts with zero, when the tire is half a meter away from the gauge. It reaches the maximum, when the center of the tire is over the gauge but does not decrease in the same manner. The remaining pressure of 0.25 bar at  $x = 60$  cm reduces to values of about 0.1 bar after some minutes and then does not change for longer time.

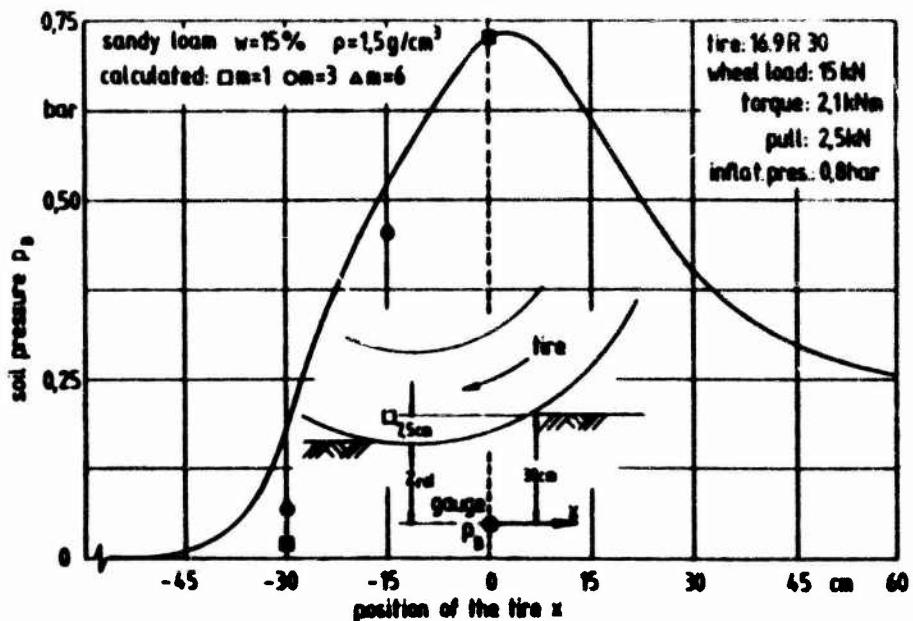


Fig. 5: Record of soil pressure  $p_B$  below a tire rolling over in the soil bin of the Institute for Agricultural Engineering of the Techn. Univ. of Munich

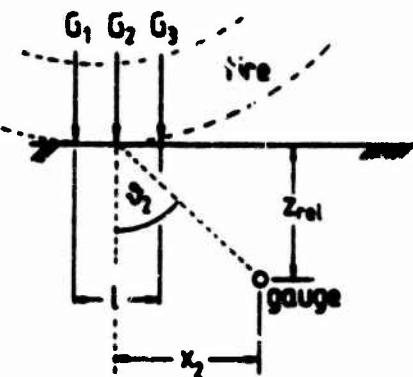


Fig. 6: Approximating the distribution of the wheel load  $G$  in the contact area of the tire by three single loads  $G_1, G_2, G_3$

Before field tests were made, it was investigated whether the one lance system (fig. 2a) could be used. Fig. 7 shows the insufficient result: The cavity caused by retracting the protecting pipe has to be filled up with compacting soil and therefore up to a sinkage  $z = 2$  cm no signal  $p_B$  is measured. Afterwards  $p_B$  is much higher than that measured with the two lance system, surely because the steel cone and the silicon tube are stiffer than the balloon and concentrate stresses on the gauge. The one lance system with supporting pipe (fig. 2b) has not yet been tested, but obviously this system avoids the problems arising with the cavity around the gauge.

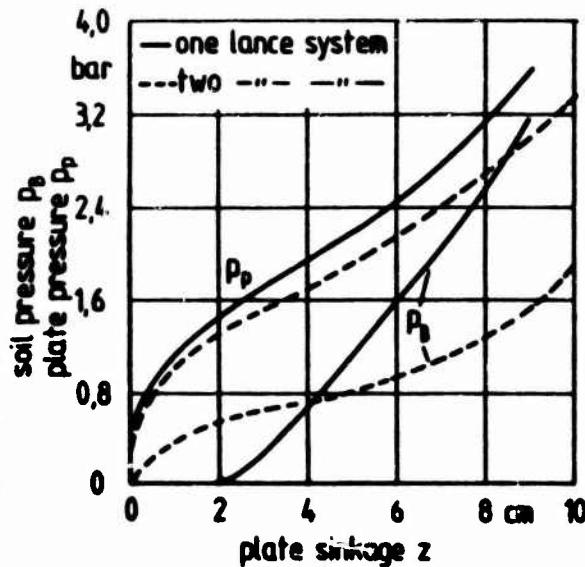


Fig. 7: Pressure  $p_b$  in sandy loam in a soil tank, measured with the one lance system (fig. 2a) and the two lance system (fig. 1)

Summarizing the important properties of the two lance system in fig. 1 one can say:

1. The bulk density of the gauge can be fitted to that of the surrounding soil by using the right fluid. (For this first tests only water was used).
2. Gauge application causes disturbances in soil as far as the drilling of the hole is concerned. The amount of time for one application is less than 15 minutes.
3. The gauge does not measure defined stress components in the soil, but on the other hand
4. the gauge orientation causes minimal errors. So only the comparison of results is possible at present.
5. Using pressure gauges in spite of manometers one is able to record dynamic processes like the roll over of a tire.
6. The costs of the gauge are of an amount of about 200 - 300 DM, if a manometer is used. (The valve was built with acryl glass, to be able to observe air bubbles rising in the pipe, when the fluid is filled in.)

## Field Tests

After introducing the measuring procedure now the results of field tests are described. First it was investigated whether the influence of wheel load is visible in field too. Three vehicles with a wide range of maximum rear wheel loads were tested. The maximum gauge pressure  $p_g$  occurring during one roll over correlated to the distance between the contact area of the tire and the gauge  $z_{rel}$  is plotted in fig. 8 for a smaller tractor D 4006 with 8.5 kN wheel load on the rear tire. The curve of the DX 140 tractor shows higher values of  $p_g$ . Its rear wheel load was twice as high than that of the D 4006. The front wheel of the Fahr 1300 combine harvester was loaded with 34.5 kN. One recognizes that redoubling the wheel load does not lead to redoubled values of the pressure  $p_g$  in a certain depth  $z_{rel}$ . Supposed  $z_{rel} = 10$  cm, and the  $p_g$ -values are related to that of the small tractor, the heavy tractor's  $p_g$  is 143 %, that of the combine 257 %.

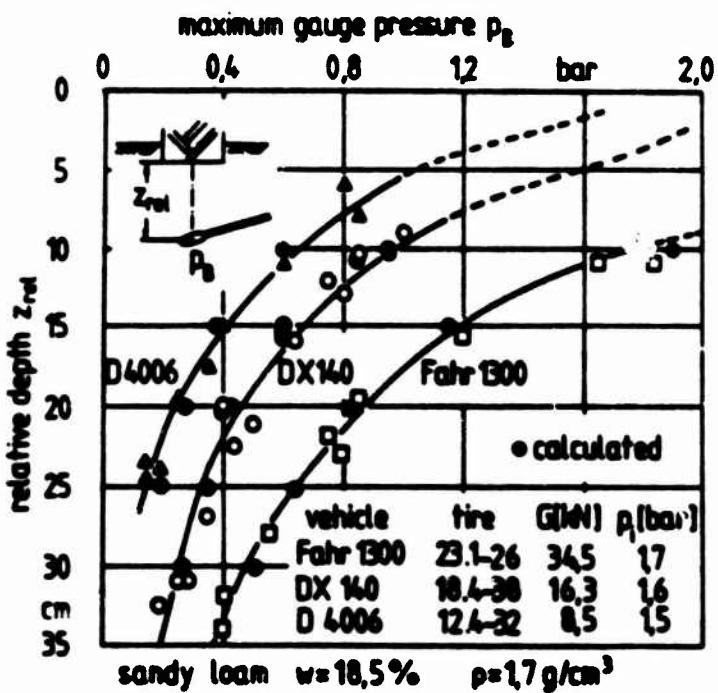


Fig. 8: Gauge pressures  $p_g$  in a sandy loam field below vehicles with fast increasing maximum rear wheel loads

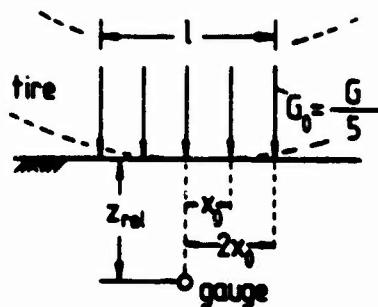


Fig. 9: Approximating the distribution of the wheel load  $G$  in the contact area of the tire length  $l$  by five uniform single loads  $G_0$

As Raghavan [9, 10, 11, 14, 15] pointed out, besides wheel load the number of passes is of essential influence on compaction. Fig. 10 shows the sinkages  $z_1$ ,  $z_5$ ,  $z_{10}$  of a tractor after the 1st, 5th and 10th roll over in the same rut. The amount of the maximum gauge pressure  $p_g$  increases from the 1st to the 5th roll over more intensive than from the 5th to the 10th. This multi-pass effect on  $p_g$  is dependent on the initial pore volume P.V. of the field. Fig. 11 shows the influence of vehicle

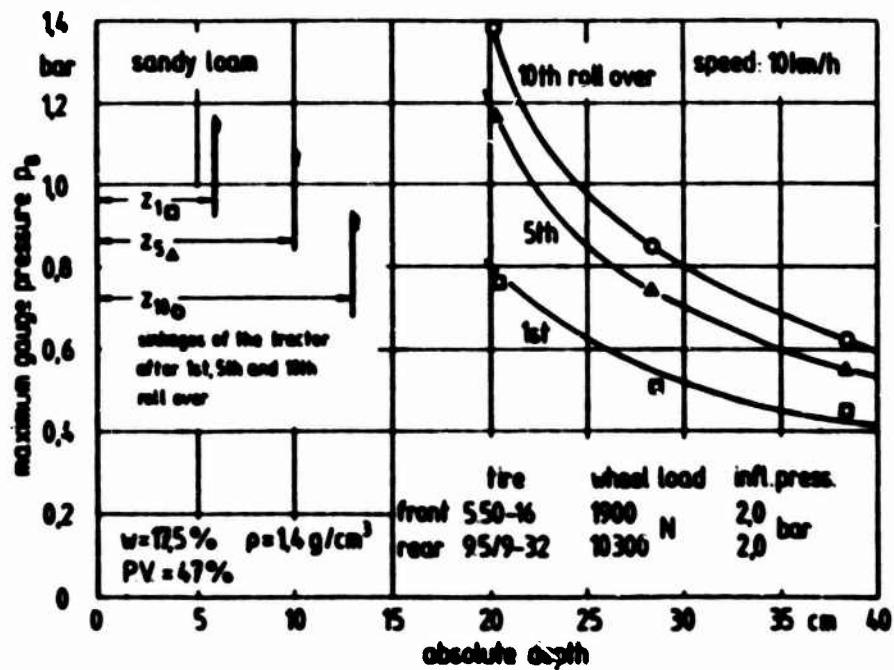


Fig. 10: Gauge pressures  $p_g$  in a field with sandy loam after one, five and ten passes

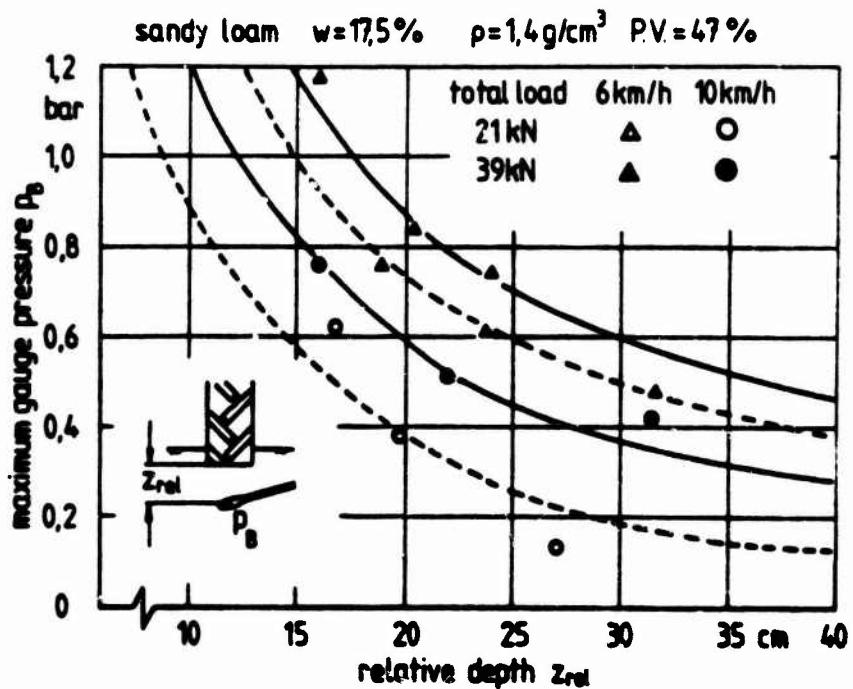


Fig. 11: Gauge pressures  $p_g$  in a soft sandy loam of high pore volume P.V. are considerably influenced by vehicle speed  
silty loam  $w=17,5\%$   $\rho=1,7\text{ g/cm}^3$  P.V.=36%

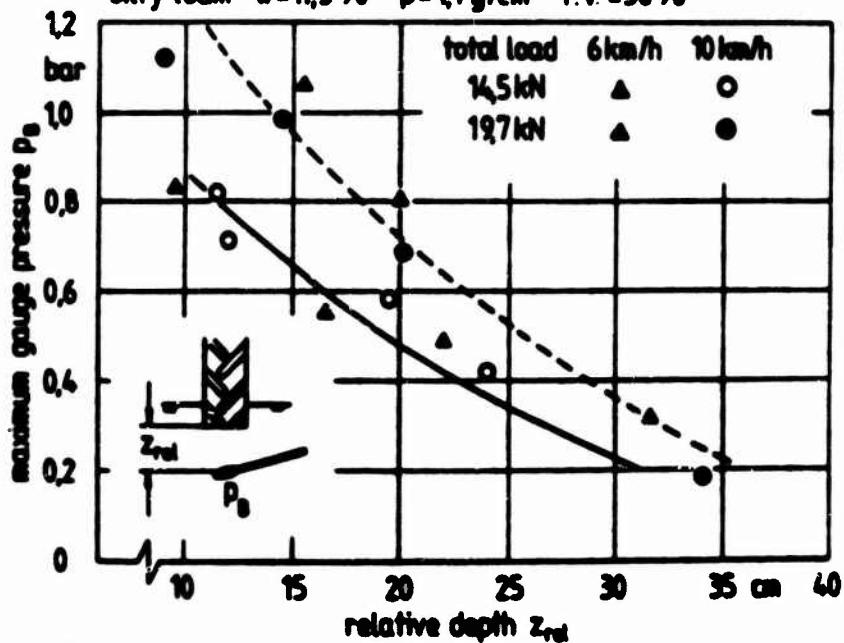


Fig. 12: Gauge pressures  $p_g$  in stiff silty loam of low pore volume P.V. are unessentially influenced by vehicle speed

speed in a soft sandy loam with high pore volume P.V. = 47 % and a dry density of  $\rho = 1.4 \text{ g/cm}^3$ . Increasing speed reduces the values of  $p_g$ . If one compares this results with those of a silty loam with higher initial dry density  $\rho = 1.7 \text{ g/cm}^3$  and a smaller amount of initial pore volume P.V. = 36 % in fig. 12, one realizes, that only wheel load makes an effect, if the pores filled with air are of considerable smaller amount. So in the silty loam field the influence of vehicle speed is not visible. Both soils had a water content of about 17.5 %. Soltynski [13] and Stafford [16] have found similar tendencies by investigating the increase of bulk density in soil below tires rolling over.

This view on some field tests should have demonstrated, that the introduced gauge is useful to compare the influence of different vehicle weights, speeds and numbers of passes on soil compaction.

#### First Simple Analytical Analysis

Now it is tried to apply the formulas stated by Soehne [1]. The vertical stress  $\sigma_z$  in a depth  $z_{\text{rel}}$  below the load axis of a circular plate of radius  $r$  with uniform load distribution  $p_p$  in a soil with the stress concentration factor  $V$  is (cf. fig. 3):

$$\sigma_z = p_p \cdot (1 - \cos \beta) \quad (1)$$

$$\cos \beta = \frac{z_{\text{rel}}}{\sqrt{r^2 + z_{\text{rel}}^2}} \quad (2)$$

$\sigma_z$  is not identical with the pressure measured by the gauge. But we know, that  $\sigma_z$  is the highest stress component appearing at the gauge. The stresses  $\sigma_z$  together with all other, smaller stress components acting on the fluid filled cylindrical balloon, produce a mean stress  $\bar{p}_g$  in it. Therefore one can state:

$$\bar{p}_g = c \cdot \sigma_z \quad 0 < c < 1 \quad (3)$$

If the plate pressure  $p_p$  is expressed by the formula describing plate sinkage tests:

$$p_p = k \cdot \left( \frac{z}{z_0} \right)^n \quad (4)$$

we can combine formulas (1) to (4):

$$\rho_0 = c \cdot k \cdot \left( \frac{z}{z_0} \right)^n \cdot \left[ 1 - \left( \frac{z_{rel}}{\sqrt{r^2 + z_{rel}^2}} \right)^v \right] \quad (5)$$

The curves in fig. 3 are well approximated by (5), if the constants of table 1 are used:

table 1:

$\rho$ (g/cm <sup>3</sup> )	k (N/cm <sup>2</sup> )	n (-)	c (-)	v (-)	$z_0$ (cm)
1,3	4,8	0,46	0,43	6	1
1,5	9,0	0,46	0,85	5	1
1,7	15,5	0,46	0,85	4	1

( $z_0$ : reference depth)

The stress concentration factors  $v$  had been chosen analogous to those Soehne [1] used in his paper. The assumption that  $0 < c < 1$  came true.

To calculate the vertical stress  $\sigma_z$  in the distance  $x$  from the load axle of the tire in a depth of  $z_{rel}$  below its contact area, formula (6) is useful (cf. Soehne [1]):

$$\sigma_z = \frac{v \cdot G}{2\pi \cdot r_0} \cdot \cos^v \delta \quad (6)$$

$$r_0 = \sqrt{x^2 + z_{rel}^2} \quad (7)$$

$$\cos \delta = \frac{z_{rel}}{r_0} \quad (8)$$

( $v$ : stress concentration factor)

To take into account, that the wheel load  $G$  is distributed over the contact area of the length  $l$  of the tire with radius  $R$  one can use the formulas (9) and (10):

$$l = \sqrt{R^2 - (R-z)^2} \quad (9)$$

$$\sigma_z = \frac{v}{2\pi} \cdot \sum_{i=1}^n \left[ \frac{G_i}{(x_i^2 + z_{rel}^2)} \cdot \left( \frac{z_{rel}}{\sqrt{x_i^2 + z_{rel}^2}} \right)^v \right] \quad (10)$$

( $z$ : tire sinkage)

Here  $i$  is the index of a proper single load  $G_i$  shown in fig. 6.  $n$  is the number of single loads.

Regarding (3) we get the term for the gauge pressure  $p_B$ :

$$p_B = c \cdot \frac{v}{2\pi} \cdot \sum_{i=1}^m \left[ \frac{G_i}{(x_i^2 + z_{rel}^2)} \cdot \left( \frac{z_{rel}}{\sqrt{x_i^2 + z_{rel}^2}} \right)^v \right] \quad (11)$$

$$G = \sum_{i=1}^m G_i \quad (12)$$

In fig. 5 the results for  $m=1$ ,  $m=3$  and  $m=6$  are shown for the distances  $x = -30$  cm,  $-15$  cm and  $x = 0$  cm. The wheel load  $G$  was divided up into uniform single loads  $G_i$ . The constants  $c$  resulting from the calculations with a different number  $m$  of single loads shows table 2:

table 2:

$m$ (-)	$G_i$ (N)	$c$ (-)	$v$ (-)
1	15 000	0,31	5
3	5 000	0,48	5
6	2 500	0,48	5

$v$  was set to 5, because the soil bin was filled with the same sandy loam used for the soil tank tests (fig. 3). The mean density in the bin was  $\rho = 1,5$  g/cm<sup>3</sup> and the water content (dry base)  $w = 15$  %. Fig. 5 shows, that the step from  $m=1$  (1 single load) to  $m=3$  (3 single loads) improves the result of the calculation significantly, but not the step from  $m=3$  to  $m=6$ . In the latter case also  $c$  does not change. Perhaps a better fit would be reached, if the wheel load  $G$  is divided up along the contact length  $l$  and along the tire width  $B$  into single loads. The lower constants  $c$  compared with those of the soil tank tests (table 1) are imaginable, if one takes into account, that in the tank with a diameter of 0,4 m soil flow in horizontal direction is more hindered by the side walls of the tank than in the soil bin where the walls have a distance of 2,5 m. So the small main stresses in the tank will be greater than in the soil bin.

At last the field tests of fig. 8 are discussed. Because tires are concerned, the formulas (6) to (12) are used for the analysis. The sandy loam had a dry density of 1,7 g/cm<sup>3</sup> and a water content of 18,5 %. Therefore a stress concentration factor  $v = 4$  was assumed. The wheel loads acting on the rear tire were divided up into five uniform single loads  $G_i$  applying the experiences made with the evaluation of the soil bin tests. For different depths  $z_{rel}$  the pressures  $p_B$  in the load axle were calculated.

Formula (11) for this purpose becomes:

$$p_0 = c \cdot \frac{v}{2\pi} \cdot \sum_{i=1}^5 \left[ \frac{G_i}{(x_i^2 + z_{rel}^2)} \cdot \left( \frac{z_{rel}}{\sqrt{x_i^2 + z_{rel}^2}} \right)^v \right] \quad (13)$$

If symmetry is taken into account (cf. fig. 9), we get:

$$p_0 = c \cdot \frac{v}{10\pi} \cdot G_0 \cdot \left[ \frac{1}{z_{rel}^2} + \frac{2}{(x_0^2 + z_{rel}^2)} \left( \frac{z_{rel}}{\sqrt{x_0^2 + z_{rel}^2}} \right)^v + \frac{2}{(4x_0^2 + z_{rel}^2)} \left( \frac{z_{rel}}{\sqrt{4x_0^2 + z_{rel}^2}} \right)^v \right] \quad (14)$$

$$G_0 = G_i = \frac{G}{5} \quad (15)$$

Table 3 shows the constants used for the calculations and in fig. 8 the results are plotted.

table 3:

tire	rear wheel load G (kN)	sinkage z (cm)	tire	length of	single load
			radius R (cm)	contact area l (cm)	distance x (cm)
12.4-32	8,5	7,25	69,75	31,0	7,75
18.4-38	16,3	8,83	89,75	39,0	9,75
21.3-26	34,5	12,25	83,00	43,4	10,85

Best fit was achieved by putting  $c = c_f = 0,36$  in formula (14). Compared with the value of  $c$  calculated for the soil bin test (fig. 5)  $c_s = 0,48$  in the field  $c$  was lower.

This short view on mathematical description shows, that the formulas stated by Soehne [1] need only the modification with the factor  $c$ , to regard the gauge properties. Surely this few results are not adequate to give evidence about all aspects of the constant  $c$ , but it is encouraging to see, that just simple assumptions for the calculations yield good fit. Further tests, easy to do with the described gauge, will show more about the parameters influencing  $c$ . Especially the correlation between  $c$ , stress concentration factor  $v$ , dry density  $\rho$  and the water content  $w$  should be investigated.

### Conclusions

A cheap and handy gauge to measure pressures in soil below tires and pressure plates was introduced. The influence of soil density and gauge inclination on the measured pressures was shown. Tests in the soil bin proved, that the gauge can be applied in dynamic

tests. The problems arising by simplifying the test mode with one lance systems were demonstrated. In spite of the wall thickness of 0,5 mm making the inherent stiffness of the balloon negligible, several missions in field showed, that the gauge is sturdy enough for scientific purposes. Variation of wheel load, number of passes and vehicle speed yielded well distinguishable results. Some of them could be described by the well known formulas of Soehne [1]. Modifying them by a factor c and making simple assumptions about load distribution in the contact area of the tires, led to results encouraging to further tests, yielding more details about this type of pressure gauge.

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